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EFFECTIVENESS OF A SELECTED MICROCLIMATE COOLING SYSTEM IN INCREASING TOLERANCE TIME TO WORK IN THE HEAT

Application to Navy Physiological Heat Exposure Limits (PHEL) Curve V

DEPARTMENT OF THE NAVY
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The effectiveness of a passive cooling ice vest in reducing heat strain was evaluated. The SteeleVest ~~(Steele, Inc.)~~ is a canvas vest with pockets which hold frozen gel packs against the torso (total weight 5.1 kg). Eight test volunteers attempted 10, 4-hour heat exposures (five environments, with and without the vest) in hot-humid and hot-dry environments having Wet Bulb Globe Temperatures (WBGT) of 36-39°C. Dry bulb temperatures ranged from 38-49°C, with 25-80% relative humidity. Subjects wore the Navy utility uniform and exercised at 272 W. This corresponded to a work rate equivalent to the Navy PHEL Curve V. In all environments, the SteeleVest significantly reduced thermal strain, as evidenced by reduced rectal and skin temperatures, heart rate and sweat rate. Use of the SteeleVest approximately doubled tolerance times compared with tests without the vest. The gel packs lasted approximately 2 hours before they required replacement. When the hot-humid and hot-dry environments having equivalent WGBTs were compared, thermal strain was higher in the more humid environments. In addition to its effectiveness in reducing heat strain, the SteeleVest is relatively lightweight, has a low profile, requires little maintenance and is not susceptible to mechanical problems. These characteristics make it potentially feasible for shipboard use.

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BACKGROUND

Navy ships currently follow a strict heat stress prevention program. This includes engineering measures such as insulation, repair of steam leaks, and ventilation. Additionally, heat stress surveys of the various shipboard spaces are conducted routinely. Whenever dry bulb temperature in a work space exceeds 38°C (100°F), or under conditions of "unusually high heat or moisture" or "arduous work", wet bulb globe temperature (WBGT) is measured (1). The WBGT is then applied to a series of Physiological Heat Exposure Limits (PHEL) curves (2). The PHEL curve chart is included as Appendix B. Each of the six curves (I-VI) represents a different time-weighted metabolic rate ranging from 177 to 293 W. Given the actual shipboard duty and the work-rest cycle, tables are available for selecting the appropriate curve. For all curves, it is assumed that the Navy utility uniform or work coverall is worn. Based on the work rate and the WBGT, the PHEL curves establish *maximum safe exposure* times for shipboard personnel. If the scheduled duration of a duty period exceeds the safe exposure time established by the curve, personnel must be rotated out of the heat stress area and given prescribed recovery periods. The recovery site should be an area where the WBGT is 22°C (72°F) or less, and the relative humidity must be less than 80%. The length of the recovery period is twice the heat exposure time or 4 hours, whichever is less. The PHEL curves are strictly adhered to onboard ship; only under operational emergencies may the ship's Commanding Officer waive the curves.

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(1) USS CORAL SEA Instruction 5100.17E.

(2) U.S. Navy. Manual of Naval Preventive Medicine. Chapter 3, Ventilation and thermal stress ashore and afloat. NAVMED P-5010-3 (1988), Naval Medical Command, Washington, D.C.

The PHEL curves were developed by the Heat Stress Division of the Naval Medical Research Institute (NMRI). NMRI reviewed heat research data from numerous laboratory and field experiments in which WBGT ranged from 31 to 52°C (88 to 126°F) and time-weighted metabolic rate ranged from 88 to 146 W/m^2. From these data, they established a list of physiological "end-points" which, if reached but not exceeded, would result in "apparent but reversible" heat strain (3). The rectal temperature end-point was 39.0°C (102.2°F), or 1.6°C/h rise. The other end-points included approximately 15 cardiovascular, thermal, respiratory and subjective parameters. Maximal safe exposure times were defined by reaching at least two of these objectives. Mathematical equations were developed to predict these times as a function of WBGT and metabolic rate. The best fit equations were found to be power regression curves, which are depicted on the PHEL Chart (Appendix B).

The PHEL curves are intended to represent maximal allowable exposure times. The curves apply to cases of short-term heat exposures of up to 8 hours. They apply to personnel that are heat-acclimatized, rested and euhydrated. It is assumed that there is no prior heat injury or cumulative heat fatigue. In the presence of other stressors such as fuel combustion gases and/or other vapors, the allowable exposure times must be modified.

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(3) Dasler, A.R. Heat stress, work function and physiological heat exposure limits in man. In: Thermal Analysis-Human Comfort-Indoor Environments, National Bureau of Standards, Washington, D.C., 1977.

Previous research has shown that various types of microclimate cooling systems - including dry ice, liquid, gas and "passive" systems - can be used to reduce heat strain and increase tolerance time to work in the heat (4-15). Currently, there are

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(4) Burton, D.R. Performance of water conditioned suits. Aerospace Med. 37: 500-504, 1966.

(5) Hynes, A.G., C. Bowen, and L. Allin. Evaluation of a personal cooling ensemble using human subjects exposed to moderate and severe hot climatic conditions. Downsview, Ontario: Defence and Civil Institute of Environmental Medicine, 1981; DCIEM Report No. 81-R-37.

(6) Kamon, E. Personal cooling in nuclear power stations. Palo Alto, CA: March 1983, Electric Power Research Institute Report No. EPRI NP-2868.

(7) Kamon, E., W.L. Kenney, N.S. Deno, K.I. Soto, and A.J. Carpenter. Readdressing personal cooling with ice. Amer. Ind. Hyg. Assoc. J. 47: 293-298, 1986.

(8) Konz, S., C. Hwang, R. Perkins, and S. Borell. Personal cooling with dry ice. Amer. Ind. Hyg. Assoc. J. 35: 137-147, 1974.

(9) Nunneley, S.A. Water-cooled garments: a review. Space Life Sci. 2: 335-360, 1970.

(10) Shitzer, A., J.C. Chato, and B.A. Hertig. Thermal protective garment using independent regional control of coolant temperature. Aerospace Med. 1: 49-59, 1973.

(11) Shvartz, E. Efficiency and effectiveness of different water cooled suits - A review. Aerospace Med. 43: 488-491, 1972.

(12) Speckman, K.L., A.E. Allan, M.N. Sawka, A.J. Young, S.R. Muza, and K.B. Pandolf. Perspectives in microclimate cooling involving protective clothing in hot environments. Int. J. Ind. Ergonomics 3: 121-147, 1988.

(13) Terrian, D.M., and S.A. Nunneley. A laboratory comparison of portable cooling systems for workers exposed to two levels of heat stress. Brooks Air Force Base, TX: USAF School of Aerospace Medicine, 1983; Technical Report No. USAFSAM-TR-83-14.

(14) Veghte, J.H. Efficacy of pressure suit cooling systems in hot environments. Aerospace Med. 36: 964-967, 1965.

(15) Webb, P. Thermoregulation in actively cooled working men. In: Physiological and Behavioral Temperature Regulation, edited by J.D. Hardy, A.P. Gagge, and J.A.J. Stolwijk. Springfield, IL: Thomas, 1970, p. 756-774.

a number of these systems that are commercially available. At the request of the Navy Science Assistance Program (NSAP), the Navy Clothing and Textile Research Facility (NCTRF) has evaluated a number of these systems for their potential use onboard ship. In 1987, NCTRF conducted shipboard evaluations to examine feasibility, logistics, reliability and acceptance of five commercially available cooling systems (16, 17). The systems utilized two concepts of cooling - liquid and air. The liquid-cooled systems consist of a torso vest (or vest and head cap) lined with channels through which a cooled liquid flows. A backpack or hand-carried assembly contains a motor/pump, battery and cooling medium (ice or frozen canisters). The air-cooled systems consist of a torso vest with a perforated interior through which cooled air flows. The vest is tethered to a low pressure air line. Depending on the pressure and temperature of the incoming air, a vortex tube may be used to further cool the air. During the shipboard evaluation in 1987, two of the commercial systems we tested - one air-cooled and one liquid-cooled - were found to be potentially feasible and accepted by shipboard personnel. However, because of the limitation on mobility imposed by the tether cord of the air-cooled system, only the portable liquid-cooled system - the ILC Dover, Inc. Model 1905 Cool Vest - was recommended for near-term shipboard use. Several months after the shipboard testing, NCTRF conducted a laboratory evaluation to examine the ability of the ILC Cool Vest to reduce thermal strain and to compare the ILC with another liquid-cooled system, the Life Support Systems, Inc. (LSSI) Cool Head (18). The two systems were found to be equally effective in reducing heat strain, but due to its simpler, more reliable operation and much lower cost, the ILC was recommended over the LSSI.

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(16) Janik, C.R., B.A. Avellini, and N.A. Pimental. Microclimate cooling systems: a shipboard evaluation of commercial models. Natick, MA: Navy Clothing and Textile Research Facility, 1988; Technical Report No. 163.

(17) Giblo, J., and B.A. Avellini. Outfitting Navy ships with microclimate cooling systems: an engineering evaluation to determine the initial costs. Natick, MA: Navy Clothing and Textile Research Facility, 1989; Technical Report No. NCTRF 174.

(18) Pimental, N.A., B.A. Avellini, and C.R. Janik. Microclimate cooling systems: a laboratory evaluation of two commercial systems. Natick, MA: Navy Clothing and Textile Research Facility, 1988; Technical Report No. 164.

In 1988, NSAP requested that NCTRF evaluate an additional type of cooling system, which has been described as a "passive" cooling vest. These vests contain pockets which hold frozen gel packs against the torso. This type of system is simple to use and contains no moving parts or batteries; it would be particularly suitable for shipboard use where individual cooling systems may be used for 8-12 hours each day. In March 1988, a laboratory evaluation was conducted to compare two commercially available passive cooling systems - the Steele, Inc. SteeleVest and the American Vest Company Stay Cool Vest - to the liquid-cooled system (ILC Dover Cool Vest) previously tested and recommended (19). Of the three systems, two - the passive cooling SteeleVest and the liquid-cooled ILC Dover - were found to be similarly effective in reducing thermal strain. Both systems enabled subjects to perform moderate exercise for 3 hours in a 43°C (110°F), 45% rh environment. The American system was not nearly as effective as the Steele or the ILC Dover. This may have been due to two reasons: the smaller surface area of the frozen gel packs, and poor contact between the gel packs and the body. In this evaluation, the Steele used more coolant by weight (70%) and by volume (20%) than the ILC. However, the ILC system also had several disadvantages: it is bulkier and slightly heavier than the Steele and, because it is battery-operated and mechanical in nature, it requires more maintenance and is more prone to operational difficulties than the Steele. For these reasons, the SteeleVest was recommended over the ILC for potential shipboard use. During the summer of 1988, a number of SteeleVests were used on ships in the Persian Gulf and were favorably received (S. McGirr, NSAP, personal communication).

Part of the decision on whether the Navy will institute widespread use of a microclimate cooling system onboard ship may be based on being able to develop a table of recommended safe exposure times to reflect the increased tolerance times when the systems are used. If stay times and/or work efficiency cannot be significantly increased by the use of a cooling system, it is doubtful that the Navy will incur the expense of these systems "merely" to increase personal comfort. The primary purpose of the present evaluation, therefore, was to begin evaluating the increases in tolerance time when a selected microclimate cooling system - the SteeleVest - is used in various environments. In the present evaluation, one metabolic rate was used, which corresponded to PHEL Curve V (the second highest of the six work rates represented by the PHEL curves). Five environments were examined, encompassing WBGT conditions ranging from 36-39°C (96-102°F). Although the WBGT range was small, dry bulb temperatures ranged from 100-120°F, and humidity 25-80%. Because of this, it was expected that within this relatively small WBGT range,

(19) Pimental, N.A., and B.A. Avellini. Effectiveness of three portable cooling systems in reducing heat stress. Natick, MA: Navy Clothing and Textile Research Facility, 1989; Technical Report No. NCTRF 176.

there might be large differences in tolerance time with the cooling vest. Some of the tested environments were chosen to simulate environmental conditions typical of ships operating on the Atlantic Coast during the summer months. Under these combinations of WBGT and work rate, the current PHEL curves limit exposure time to 60-95 minutes.

The secondary purpose of the present evaluation was to compare thermal responses and tolerance times in equivalent WBGT environments. Maximum exposure times established by the PHEL curves are the same for environments having equivalent WBGT's. Some research, however, has shown that physiological responses to equivalent WBGT conditions are not necessarily equivalent, particularly when hot-humid and hot-dry environments are compared (20, 21). Under our test design, therefore, we chose humid and dry environments that produced equivalent WBGT's.

METHODS

Description of Cooling System: The SteeleVest is manufactured by Steele, Inc., of Kingston, WA. The vest has six pockets (three in front, three in back) with Velcro closures, which hold 5- or 9-ounce frozen gel packs (see Figure 1). The gel packs contain mainly a cornstarch and water mixture. The vest has a cotton canvas shell and the pockets are externally insulated with Thinsulate. In the present evaluation, the 9-ounce gel packs were used, making the total weight of the system 5.1 kg (11.2 lbs) (4.6 kg of gel packs plus vest). The vest comes in one size only; two Velcro straps are used to tighten the vest around the torso. As of August 1988, the cost of the SteeleVest with one set of gel packs was $150; each additional set of six gel packs was $54.

Test Design: Eight healthy male subjects participated in the evaluation (average age, 26 yr; height, 174 cm; weight, 70.0 kg). They were informed of the purpose, procedures and risks of the study, and of their right to terminate participation at will without penalty. Each expressed understanding by signing a statement of informed consent. For 1 week prior to testing, the subjects were heat acclimated by daily, 2-hour heat exposures in a climatic chamber. Environmental conditions alternated daily between hot-dry (49°C=120°F, 20% rh) and hot-humid (35°C=95°F, 75% rh).

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(20) Armstrong, L.E., et al. Physiological responses to WBGT-equivalent environments and two clothing types during simulated desert marches. Natick, MA: US Army Research Institute of Environmental Medicine, 1985; Technical Report No. T4/86.

(21) Shapiro, Y., K.B. Pandolf, B.A. Avellini, N.A. Pimental, and R.F. Goldman. Physiological responses of men and women to humid and dry heat. Journal of Applied Physiology: Respiratory Environmental and Exercise Physiology 49: 1-8, 1980.

During the acclimation exposures, subjects wore the Navy utility uniform and walked on a level treadmill at 1.6 m/s (3.5 mph). Following the week of heat acclimation, each subject participated in 10 tests - with and without the cooling vest in five different environments (repeated measures design with each subject serving as his own control). The order of presentation of the environments was randomized by day (not by subject, because the eight subjects were tested simultaneously). On any test day, half of the subjects used the cooling vest and half did not. The five environments are listed below. The designation for each environment denotes the WBGT (°C) and "H" for the more humid, and "D" for the drier of the two equivalent WBGT environments.

Dry bulb, % rh	WBGT	Designation
38°C (100°F), 80% rh	36°C (96°F)	WBGT36H
49°C (120°F), 25% rh	36°C	WBGT36D
43°C (110°F), 60% rh	38°C (100°F)	WBGT38H
49°C (120°F), 35% rh	38°C	WBGT38D
49°C (120°F), 39% rh	39°C (102°F)	WBGT39

Wind velocity was 1.0 m/s (2 mph). Subjects attempted to complete 4 hours of heat exposure, during which they walked on a level treadmill at 1.3 m/s (3 mph) for 25 minutes and sat for 5 minutes every half hour. They wore the Navy utility uniform, consisting of denim trousers, long-sleeved cotton chambray shirt and T-shirt plus underwear, socks and sneakers (thermal insulation, or clo value of ensemble = 1.1; water vapor permeability, or i_m value = 0.6). When the cooling vest was used, it was worn over both the T-shirt and the chambray shirt.

Measurements: Rectal temperature was measured with a thermistor probe inserted 10 cm (4 in) beyond the anal sphincter. Skin temperatures were measured using thermocouples on the chest, arm and leg; mean weighted skin temperature was calculated with the formula of Burton (22). Rectal and skin temperatures were printed and plotted every 2 minutes with a computer-controlled data acquisition system. The electrocardiogram was obtained from chest electrodes and continuously displayed on an oscilloscope and cardiotachometer unit. Heart rates were recorded twice each half hour, at 15 and 25 minutes of each 25-minute walk bout. Oxygen uptake was measured with open-circuit spirometry. Total body sweating rate was calculated from pre- and post-test nude body weights, adjusted for water consumption. Subjects were encouraged to drink water during the heat exposures to prevent significant dehydration. Every half hour, subjects were asked to numerically rate their thermal sensation using a nine-point temperature sensation scale ranging from -4 ("very cold") to +4 ("very hot") (0 = "neutral").

(22) Burton, A.C. Human calorimetry II. The average temperature of the tissues of the body. Journal of Nutrition 9: 261-280, 1935.

The gel packs were frozen in an environmental chamber at -22°C (-8°F). During testing, the gel pack temperature was measured using thermocouples placed against two of the gel packs (one pack in front of the vest, one in back). When the gel pack temperature reached approximately 20°C (68°F), the packs were replaced. The packs were also checked manually to ensure that they were replaced when almost melted. The time of each coolant change was recorded.

During any test, a subject was removed from the heat exposure if his rectal temperature reached 39.0°C (102.2°F), or if his heart rate exceeded 180 b/min for 5 minutes continuously. A subject was also removed if he was unable to continue walking unassisted. Most often, this occurred due to dizziness and/or nausea.

Statistical Analysis: The data were statistically analyzed by the use of repeated measures analyses of variance. In order to compare the SteeleVest with the control data, separate analyses were performed on the data from each of the five environments. The exposure time and the sweating rate data were analyzed by one-way analyses of variance (control versus cooling vest). The rectal temperature, skin temperature, heart rate and thermal sensation data were analyzed by two-way analyses of variance (control versus cooling vest / time). Because the number of subjects decreased during the heat exposures, statistical comparisons could be made only up to the following times: 60 minutes (WBGT38H), 80 minutes (WBGT36H and WBGT39), 100 minutes (WBGT38D), and 240 minutes (WBGT36D). Within these times, missing values due to subject attrition were estimated with least squares, and the degrees of freedom were adjusted accordingly. Data points were not estimated after more than three of the eight subjects dropped out, and no more than 10% of the data points within an analysis were estimated. Tukey's test was used to locate the significant differences; significance was accepted at the 0.05 level.

In order to compare the humid with the dry environment data (at equivalent WBGT's), separate statistical analyses were performed on the control and SteeleVest data. Because of subject attrition, the data were analyzed only up to the following time periods: 80 minutes (WBGT36D and WBGT36H, control), 180 minutes (WBGT36D and WBGT36H, SteeleVest), 60 minutes (WBGT38D and WBGT38H, control) and 100 minutes (WBGT38D and WBGT38H, SteeleVest).

RESULTS

Exposure Time: Exposure times (means $\pm$ SD) in each of the five environments for the control and SteeleVest tests are presented in Figure 2. (Maximum exposure time in this evaluation was limited to 240 minutes.) With the SteeleVest, exposure times were significantly higher than control in all cases ($p<0.05$), except in WBGT36D, where most subjects (6 of 8) were able to complete the 240-minute exposure even during the control test. Of the total of 57 times when heat exposures were terminated early, half were due to reaching the pre-determined rectal temperature limit of 39.0°C. Other causes of early termination included inability to continue walking unassisted due to nausea (14%), dizziness (12%), or a combination of the two (14%), and reaching the heart rate limit (9%). Average exposure times for each of the test conditions are listed in Table C-1 of Appendix C.

Comparing WBGT38D with WBGT38H, we found exposure time was significantly higher in the drier of the two environments for both the control and the SteeleVest tests. In the 36°C WBGT condition, exposure time was higher in the drier environment for the control test. Because maximum exposure time was limited to 240 minutes, there was no significant difference between the dry and the humid environments when the SteeleVest was used at 36°C WBGT.

Rectal Temperature: Figures 3-5 illustrate rectal temperature responses during the control tests and when the SteeleVest was used in each of the environments. Data from the 36°C, 38°C and 39°C WBGT environments are plotted in Figures 3, 4 and 5, respectively. (The data are plotted until six of the eight subjects remained.) In all environments, there were significant differences in the rectal temperatures when the control and the SteeleVest tests were compared. In the WBGT36H, 38D, 38H and 39 environments, these differences were statistically significant after the first 20 minutes of heat exposure. In the fifth environment (WBGT36D), the differences were significant after the first 60 minutes. In all cases, the increase in rectal temperature from the initial value when the SteeleVest was used was less than the increase during the control test ($p<0.05$). Table C-2 (Appendix C) lists changes in rectal temperature for the control and the SteeleVest tests.

When the equivalent WBGT environments were compared, the increase in rectal temperature was less in the drier than in the more humid environment, from 40 minutes on ($p<0.05$). This was true for both the 36 and 38°C WBGT conditions both for the control and the SteeleVest tests. (When the SteeleVest was used in the 36°C WBGT condition, this was significant from 60 minutes on.)

Skin Temperature: Mean weighted skin temperatures in the 36, 38 and 39°C WBGT environments are shown in Figures 6, 7 and 8, respectively. The increases and decreases in mean weighted skin temperature for the SteeleVest tests occurred as the gel packs melted and were then replaced. From 20 minutes on, in each of the environments, mean skin temperature was lower when the SteeleVest was used than during the control test ($p<0.05$). Mean weighted skin temperatures are shown in Table C-3 (Appendix C).

In both WBGT environments, mean weighted skin temperature during the control test was also significantly lower after the first 20 minutes of heat exposure in the drier than in the more humid environment. When the SteeleVest was used in the 36°C WBGT environment, skin temperature was significantly lower in the drier condition only during the second hour of heat exposure. When the SteeleVest was used in the 38°C WBGT environment, there were no statistically significant differences in skin temperature between the dry and the humid environments.

Heart Rate: Heart rates during each of the heat exposures are presented in Figures 9-11. In each environment, heart rate was significantly lower when the SteeleVest was used than during the control tests.

In the WBGT36H environment, heart rates were significantly lower with the SteeleVest from 30 minutes on. In the WBGT36D environment, there were no differences during the first 60 minutes of heat exposure; with the exception of 110 minutes, heart rate was lower with the SteeleVest from 80 minutes on. Heart rates were lower with the SteeleVest at all time periods in the WBGT38H and WBGT39 environments. In the WBGT38D environment, heart rate was lower with the SteeleVest from 50 minutes on. The heart rate data are presented in Table C-4 (Appendix C).

In both the 36 and 38°C WBGT environments, heart rates were lower after the first 20 minutes of heat exposure in the drier than in the more humid condition ($p<0.05$). (When the SteeleVest was used in the 36°C WBGT environment, this difference was significant after the first 30 minutes.)

Sweat Rate: Figure 12 illustrates total body sweat rates with and without the SteeleVest in each of the five environments. In each environment, sweat rate was lower when the SteeleVest was used than during the control test ($p<0.05$). The sweat rate data (expressed in $g/m^2/h$) are presented in Table C-5 (Appendix C).

In both the 36 and 38°C WBGT environments, sweat rates were significantly lower in the drier of the two WBGT-equivalent environments. This was true both when the SteeleVest was used and for the control tests. Comparing WBGT36D with WBGT36H, sweat rates were 36 and 28% lower in the drier of the two environments for the control and the SteeleVest tests, respectively. Sweat rates were 17 (control) and 30% (SteeleVest) lower in WBGT38D compared with WBGT38H.

Thermal Sensation: In all but the WBGT38H environment, significant differences were found in subjective ratings of thermal sensation. At all time periods in the WBGT36H and WBGT38D environments, the SteeleVest was rated numerically lower (i.e., cooler) than the control ($p<0.05$). In the WBGT36D environment, the SteeleVest was rated cooler during the last 2 hours of heat exposure. In the WBGT39 environment, the SteeleVest was rated cooler at 60 minutes. The thermal sensation ratings are presented in Table C-6 (Appendix C). A thermal rating of 2 corresponds to a verbal anchor of "warm"; 3 corresponds to "hot"; and 4 corresponds to "very hot".

In most cases, ratings of thermal sensation were significantly lower in the drier environment. (When the SteeleVest was used in the 36°C WBGT condition, ratings were different only during the second hour of heat exposure.)

Coolant Replacement: Average times (±SD) of gel pack replacement were 126 (±2), 141 (±7), 107 (±14), 113 (±19) and 119 (±2) minutes in the WBGT36H, 36D, 38H, 38D and 39 environments, respectively. The coolant lasted longer in WBGT36D than in 38H, 38D, or 39 ($p<0.05$). The coolant lasted longer in WBGT36H than in 38H ($p<0.05$). The average time of coolant replacement in all environments was 121 minutes.

DISCUSSION

PHEL Curve V corresponds to a time-weighted metabolic rate of 135 W/m^2, or 270 W. In the present evaluation, subjects walked on a level treadmill at 1.3 m/s for 25 minutes and sat for 5 minutes every half hour. The metabolic rate measured during the walk was 306 W; resting metabolic rate was assumed to be 105 W. The time-weighted metabolic rate, therefore, was $0.83*(306) + 0.17*(105) = 272$ W. Thus, in the present evaluation the effectiveness of the SteeleVest was examined at a metabolic rate equivalent to Curve V, the second highest of the six work rates represented by the PHEL curves.

In Table I below, actual exposure times from the control tests in the present study can be compared with exposure times established by PHEL Curve V. The '+' symbol indicates that average exposure time might have been longer had the test not been limited to 240 minutes. From the table it can be seen that for the two most humid environments (WBGT36H and 38H), our control data agree very closely with the PHEL curve. As the environment becomes drier, however, and tolerance time becomes greater, the PHEL curve underestimated exposure time by 25 to 57%. This may be because the PHEL curves set equal exposure times for environments having equivalent WBGT's. The present study, however, demonstrated that thermal strain is lower and tolerance time greater in the drier compared with the more humid environment. This is in agreement with the findings of several other researchers (20,21). In the present study, the increased heat strain in the more humid environments may have been caused by a reduction in evaporative heat loss due to the type of clothing that was worn (denim trousers, T-shirt and long-sleeved work shirt, as opposed to shorts and T-shirt only).

The PHEL curves were based on reaching two of 16 physiological "end-points". It is not likely that all 16 parameters were measured in each of the field and laboratory evaluations from which the data were derived. In the present evaluation, tolerance times were based on reaching the rectal temperature or heart rate limit (or a point when the subject was unable to continue walking unassisted). Despite potential differences in end-points between the present study and the PHEL curve, our tolerance times for the more humid environments are in close agreement with PHEL Curve V. In the drier conditions, the curve underestimated exposure time compared with our data. By underestimating rather than overestimating, however, the error in allowable exposure time is in the direction of safety. Also, it should be noted that the more humid conditions, at which the PHEL curve appears to be most accurate, are typical of most shipboard spaces.

Table I. Actual tolerance times vs. PHEL Curve V vs. SteeleVest

	WBGT36H	**WBGT36D**	**WBGT38H**	**WBGT38D**	**WBGT39**
Control	93	222+	66	111	80
PHEL V	95	95	70	70	60
SteeleVest	213+	240+	123	214+	178

In four of the five environments tested in the present study, tolerance time when the Steele cooling vest was used was about twice that of the control (see Table I above). In the WBGT36D environment, most subjects were able to complete the 240-minute heat exposure even during the control test. In that environment, therefore, the true increase in tolerance time with the SteeleVest cannot be evaluated. If the SteeleVest were used onboard ship, less frequent rotation of personnel would be required. In a 38°C (100°F), 80% rh environment (WBGT=36°C, 96° F), PHEL Curve V allows a stay time of 95 minutes. To perform an 8-hour shift requiring four workers (32 work-hours), personnel would be rotated every 95 minutes. Because recovery times equal to twice the heat exposure times are required, 12 workers would be needed. Thirty-two work-hours are performed, and an additional 63 work-hours of recovery, or lost work time, are needed. If the Steele cooling vest is used, stay time is extended to 213 minutes, and rotation of personnel occurs only twice, compared with four times, during the 8 hours. Twelve workers are still required, but work-hours of recovery time are significantly reduced, from 63 to 32 hours. At the end of the 8-hour shift, eight of the twelve workers have recovered from the heat exposure and may work another shift. Without the SteeleVest, only four of the workers are available to begin another shift right away.

Use of the SteeleVest significantly reduced thermal strain, as evidenced by lower rectal temperature, skin temperature, heart rate and sweat rate responses (Figures 3-12). Reduced thermal strain has been shown to be associated with increased cognitive, perceptual and psychomotor performance, thereby enhancing job performance and productivity. The reduced thermal strain observed in the present study was not due to differences in level of hypohydration between the control and SteeleVest tests. In the present study, water intake was encouraged during all heat exposures. Only marginal hypohydration occurred: average weight loss by the end of the heat exposure did not exceed 1.4% of body weight in any of the environments. In four of the environments, there was no significant difference in % weight loss between the control and SteeleVest tests ($p>0.05$). In the fifth environment (WBGT36D), % weight loss was statistically different but not considered physiologically significant (0.5 vs. 1.0% weight loss).

When the SteeleVest was used in the present study, total body sweat rate was reduced by 24-35% compared with control. Because sweat rate was reduced, drinking water requirements were also lowered. The reductions in sweat rate due to the SteeleVest in this study reduced drinking water requirements by 0.3-0.5 liters/hour/man. This may be advantageous onboard ship, where personnel work in hot spaces for extended periods of time and dehydration is a concern.

In both this and other research, the SteeleVest has been shown to decrease thermal strain (23, 24). In testing to date, subjective data on the SteeleVest have also been positive. In the present evaluation, subjects reported that they felt cooler with the SteeleVest than without it in all but the most severe environment. In a previous laboratory test comparing the SteeleVest with two other cooling systems, the SteeleVest was rated cooler than no cooling at all and cooler than one of the other two cooling systems; ratings were equal to those of the third system (19). Six of the eight test volunteers rated the Steelevest as their overall preference of the three cooling systems. The NSAP office has also received positive comments from shipboard personnel using the SteeleVest in the Persian Gulf, where approximately 40 vests were used on 12 ships during the summer of 1988 (S. McGirr, NSAP, personal communication).

With a microclimate cooling system, there are logistical concerns to be addressed. These are detailed in a previous report (17). The SteeleVest uses a coolant (gel packs) which requires freezer space. In the present evaluation, the gel packs were frozen to $-22^{o}C$ ($-8^{o}F$). Under our test conditions, the frozen packs lasted 107-141 minutes, averaging 121 minutes. If the gel packs are not frozen to as low a temperature, coolant life will be shorter. If the environment is hotter or the work rate higher, the coolant will also have to be replaced more often. If space is not available in the ship's food freezer, a separate blast freezer may be needed (17).

One advantage of the SteeleVest compared with other cooling sytems is that it does not use batteries, which require storage and recharging. Because of its simple "passive" cooling design, the SteeleVest is easy to use and virtually unsusceptible to mechanical problems. It is portable, rugged and can be machine laundered. It weighs 5.1 kg and has a relatively low profile.

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(23) Glenn, S.P., P.A. Jensen, J.B. Hudnall, W.D. Eley, and C.S. Clark. An evaluation of three cooling systems used in conjunction with the U.S. Coast Guard Chemical Response Suit. American Industrial Hygiene Conference, St. Louis, MO, May 1989.

(24) Banta, G.R. Helicopter in-flight heat strain and effect of passive microclimate cooling. Aviat. Space Environ. Med. 61: 467, 1990.

The price of the SteeleVest compares well with other commercial cooling systems. Of the six systems we have evaluated, only the American Stay Cool Vest, which was not nearly as effective as the other systems in reducing heat strain, is less expensive than the SteeleVest. As of Feb 88, the price of the SteeleVest was $204 (vest with one set of gel packs, $150; additional set of gel packs, $54). The American vest (Feb 88) was $60 (vest with one set of gel packs, $40; additional set of gel packs, $20). The ILC Dover system (Jan 88) was $359 (vest with one battery, $249; additional battery $55; battery charger, $55). The LSSI system (1987) was $2494 (vest/backpack, $2073; four canisters, $44; two batteries, $260; battery charger, $48; refill kit, $51; quart of circulating fluid, $18). As of 1986, the price of the Encon air vest system was $393 (air vest, $200; pressure regulator, $60; air filter, $65; 50-foot hose, $50; breakaway fittings, $18). When used with a vortex tube, the Encon air vest system costs $595 (above plus vortex tube with belt, $202). Quantity discounts are available for some of the systems.

SUMMARY AND CONCLUSIONS

The effectiveness of the SteeleVest cooling system was examined at a metabolic rate equivalent to PHEL Curve V in WBGT environments ranging from 36 to 39°C. The SteeleVest was found to significantly reduce thermal strain, as evidenced by reduced rectal and skin temperatures, heart rate and sweat rate. Under these conditions, tolerance times when the SteeleVest was used were about twice those of the control tests. Although microclimate cooling should not be substituted for engineering measures in the control of shipboard heat stress, the SteeleVest may be effective in extending safe exposure times. Future testing of the SteeleVest should be conducted to examine its effectiveness under conditions of higher radiant heat load, and at different work rates.

Appendix A. Illustrations

FIG. 1. SteeleVest with gel packs.

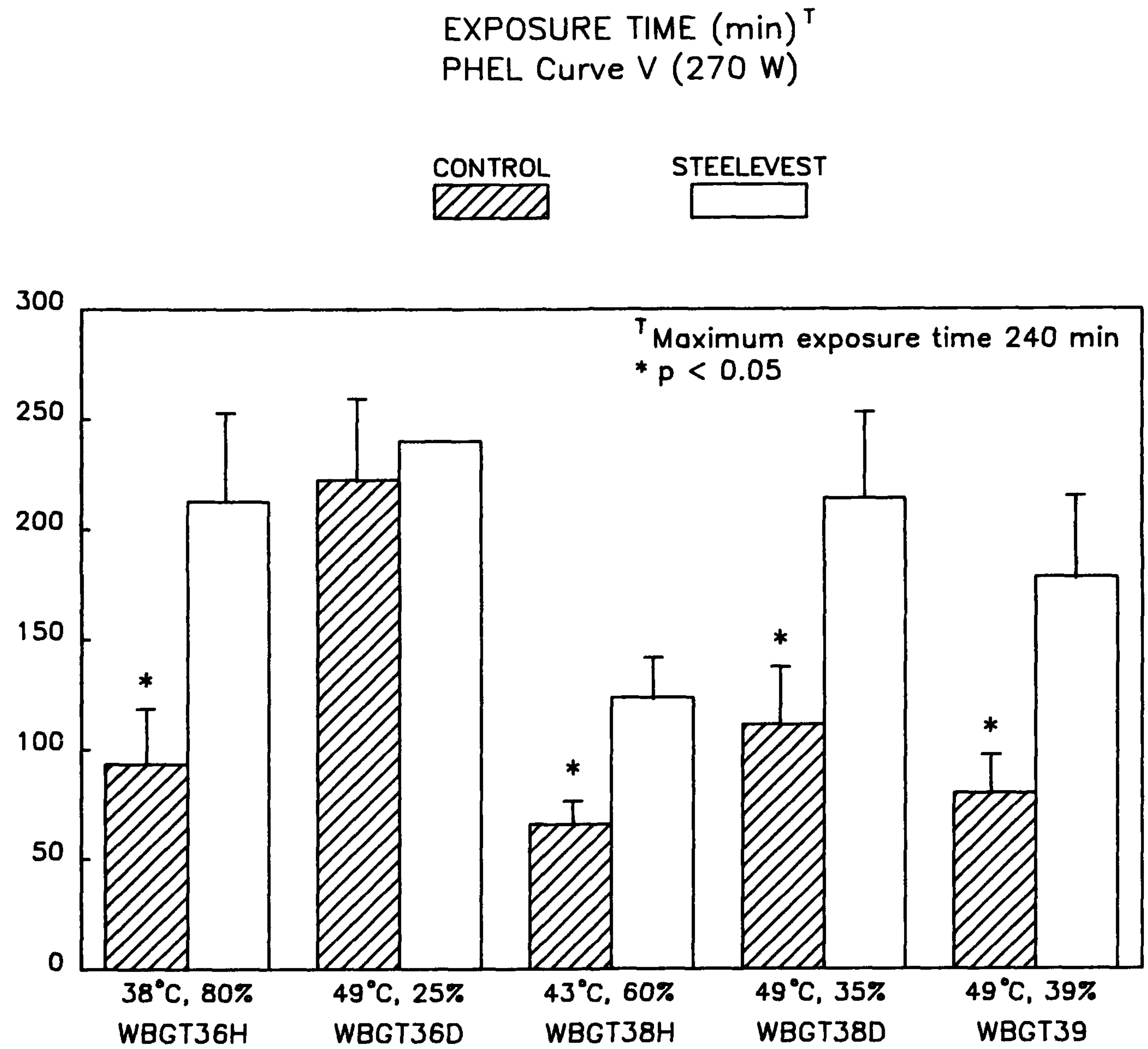


FIG. 2. Exposure time with and without the SteeleVest. T indicates SD.

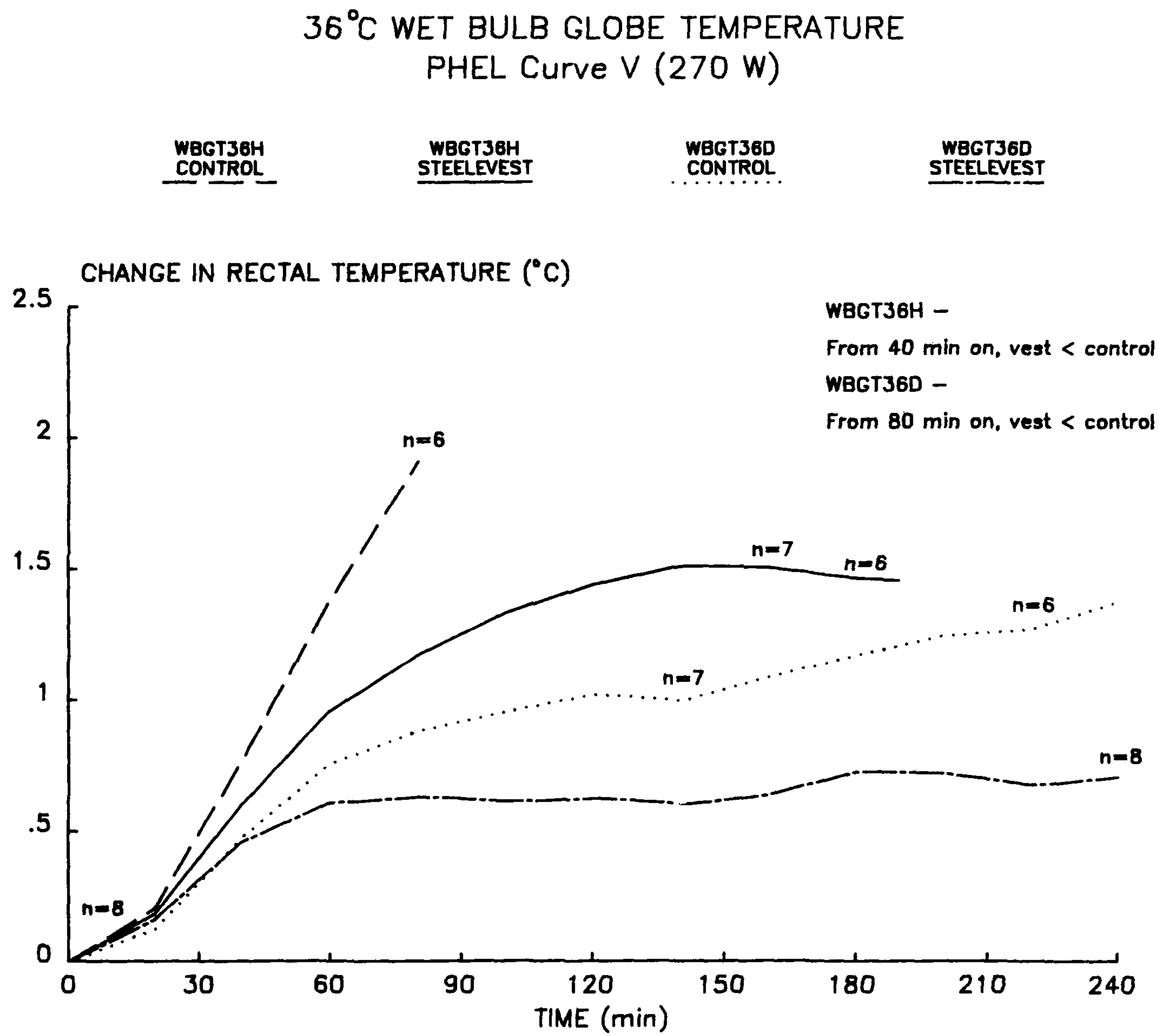


FIG. 3. Change in rectal temperature with and without the SteeleVest.

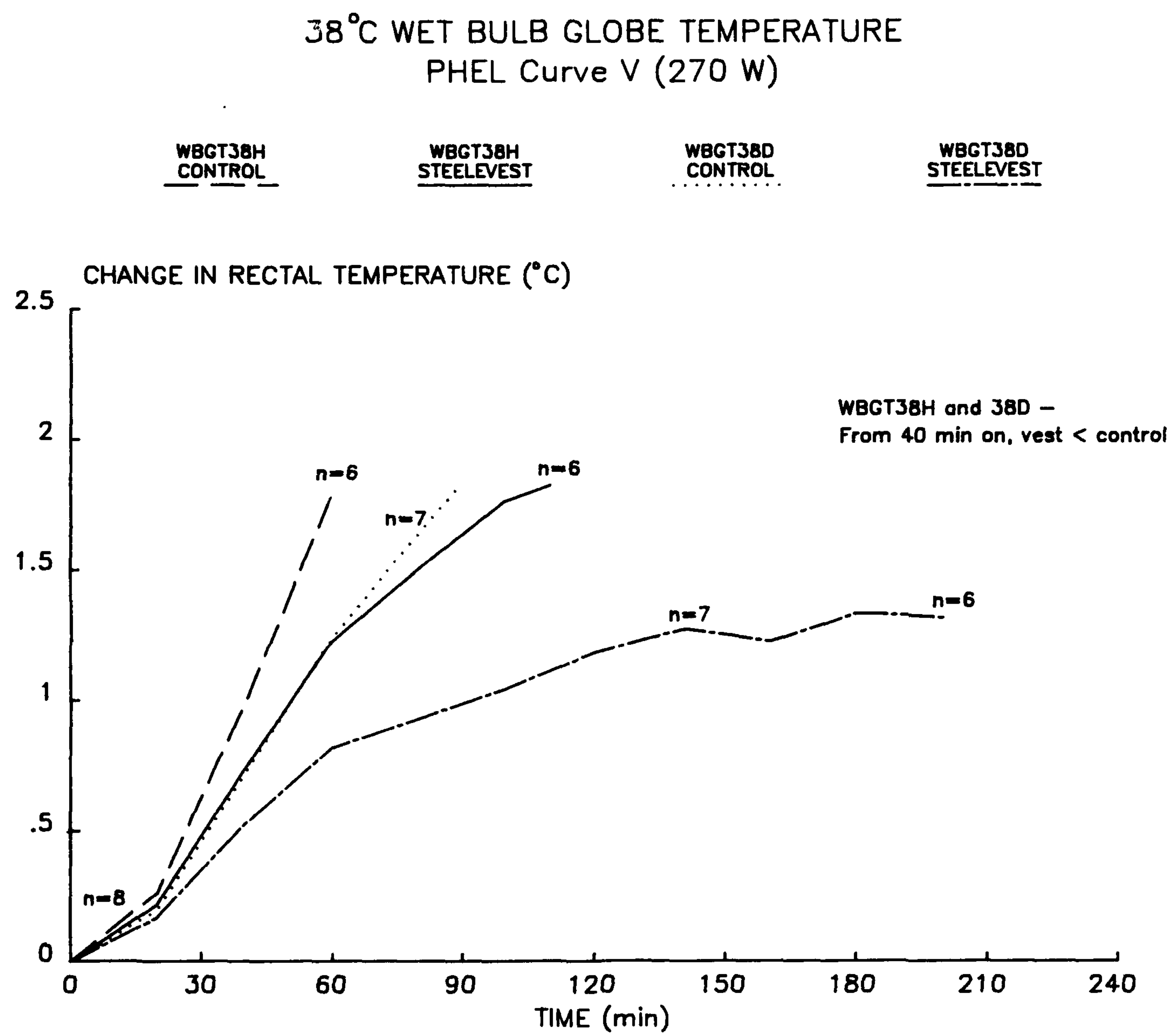


FIG. 4. Change in rectal temperature with and without the SteeleVest.

39°C WET BULB GLOBE TEMPERATURE
PHEL Curve V (270 W)

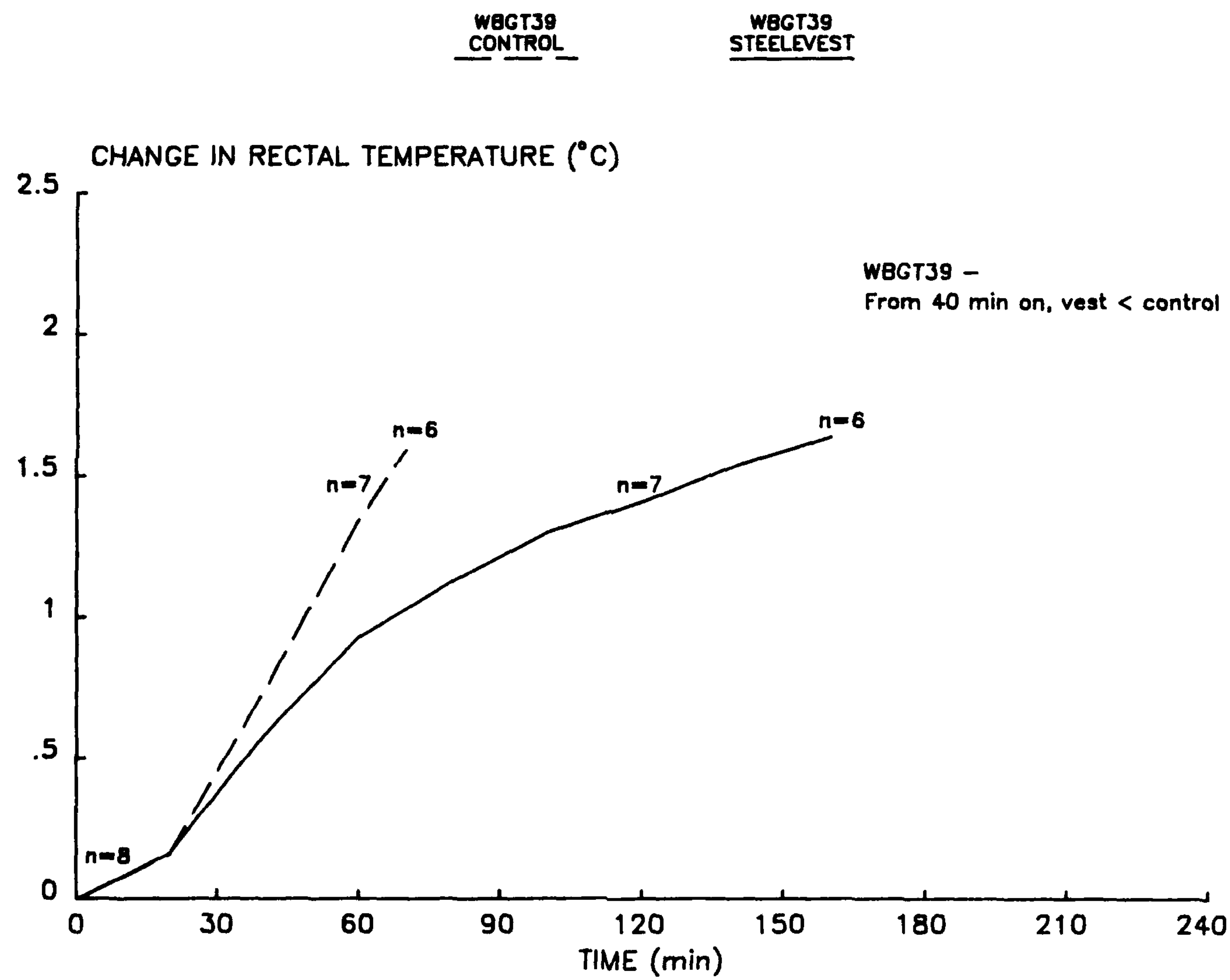


FIG. 5. Change in rectal temperature with cnd without the SteeleVest.

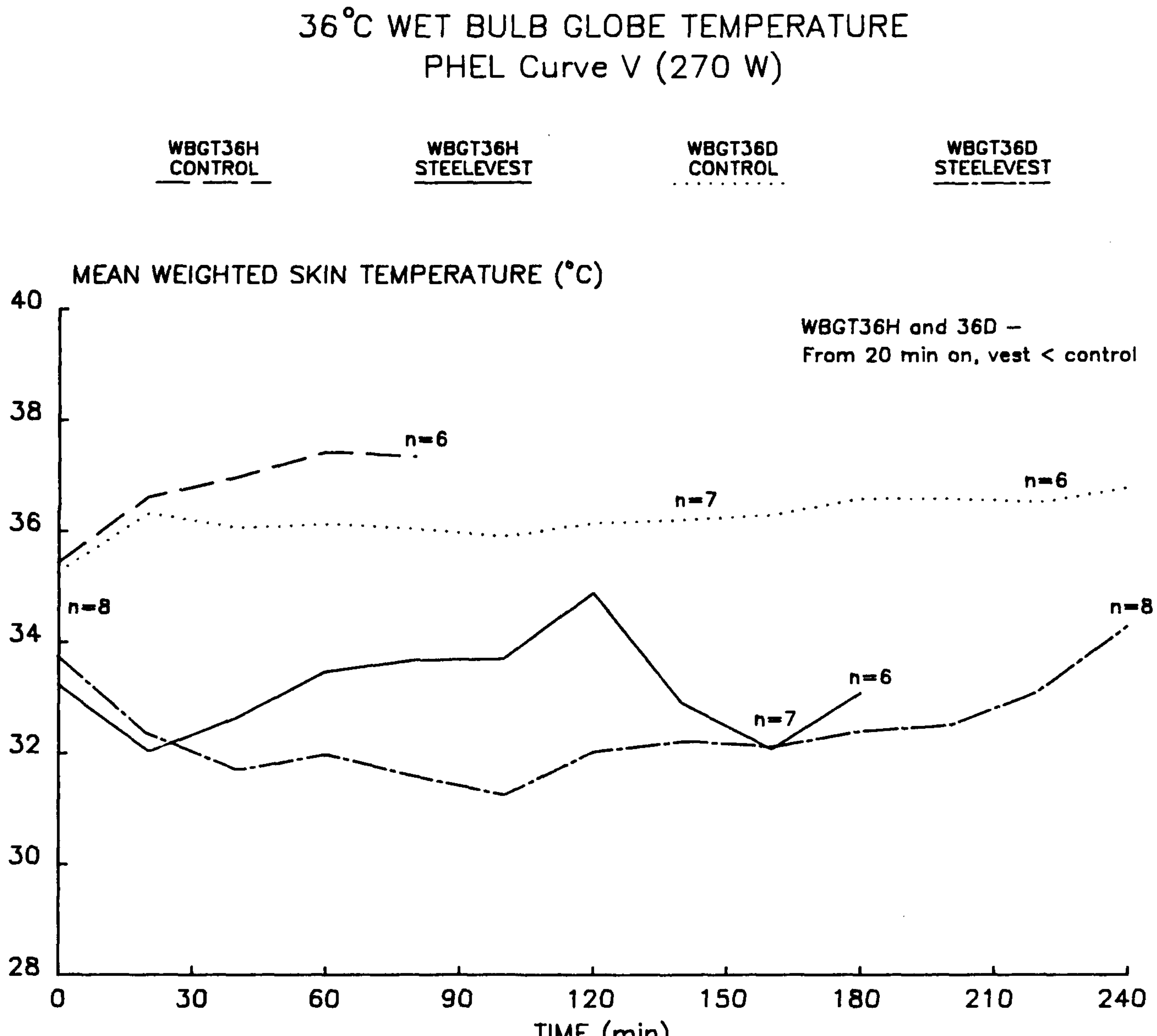


FIG. 6. Mean weighted skin temperature with and without the SteeleVest.

38°C WET BULB GLOBE TEMPERATURE
PHEL Curve V (270 W)

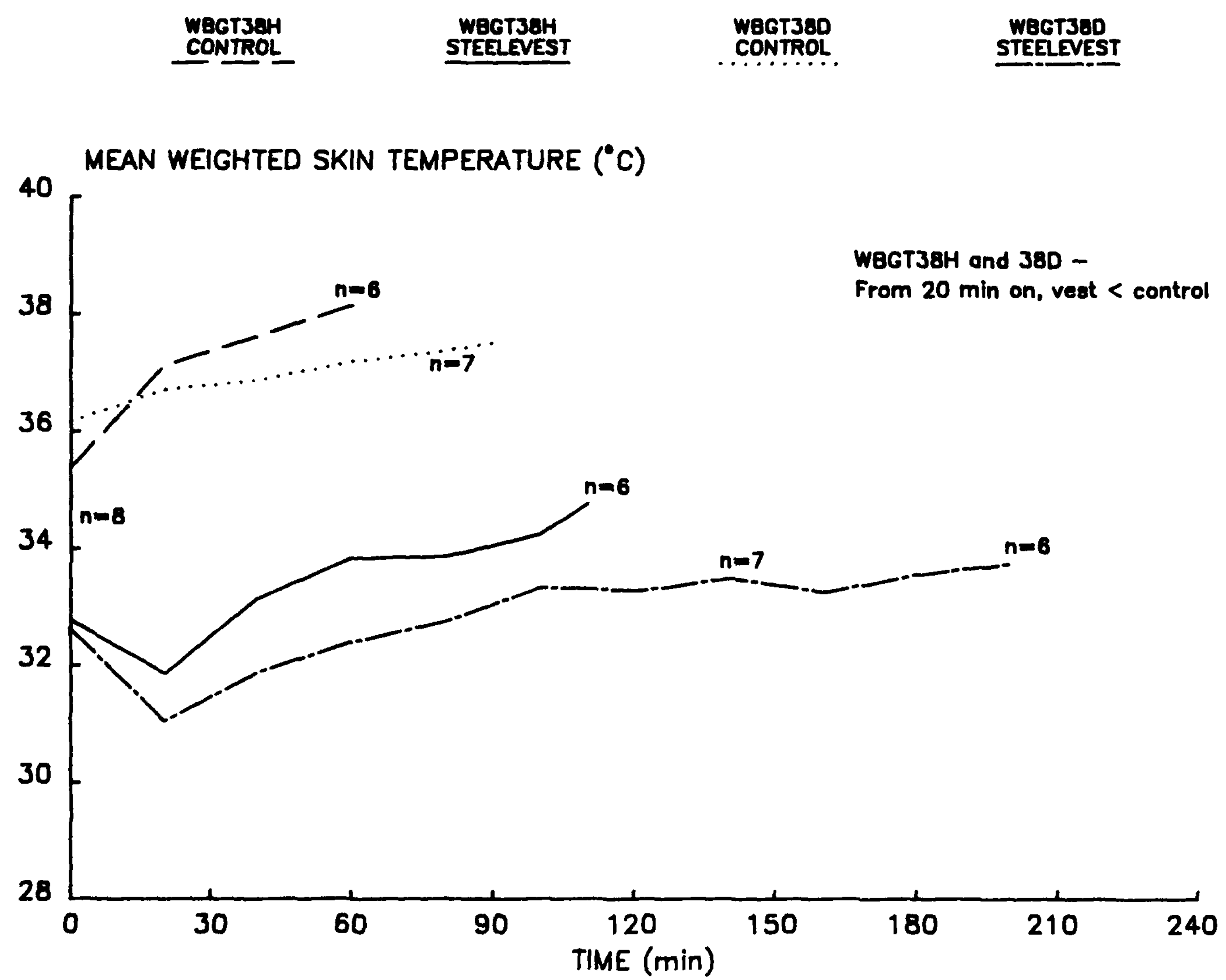


FIG. 7. Mean weighted skin temperature with and without the SteeleVest.

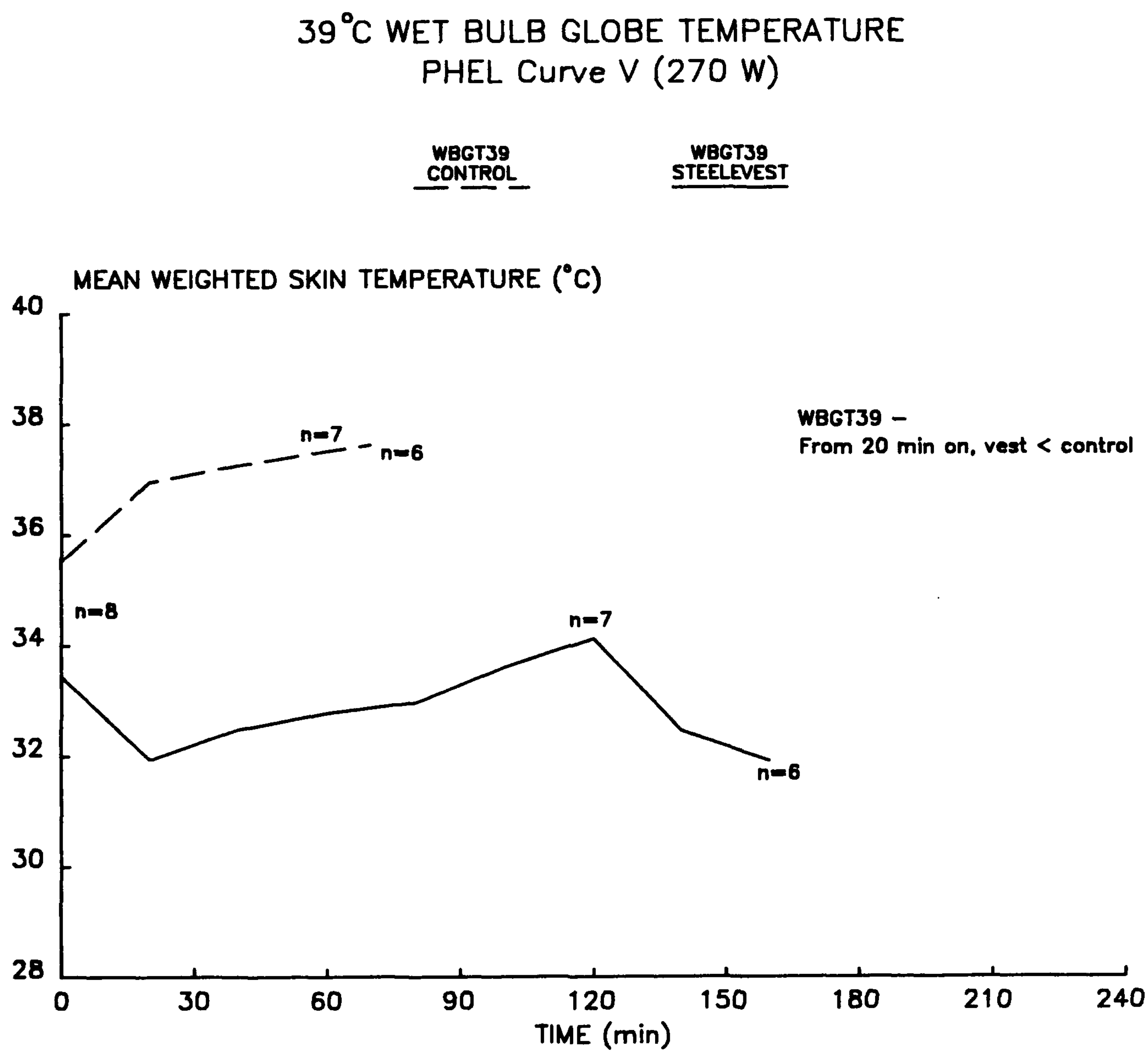


FIG. 8. Mean weighted skin temperature with and without the SteeleVest.

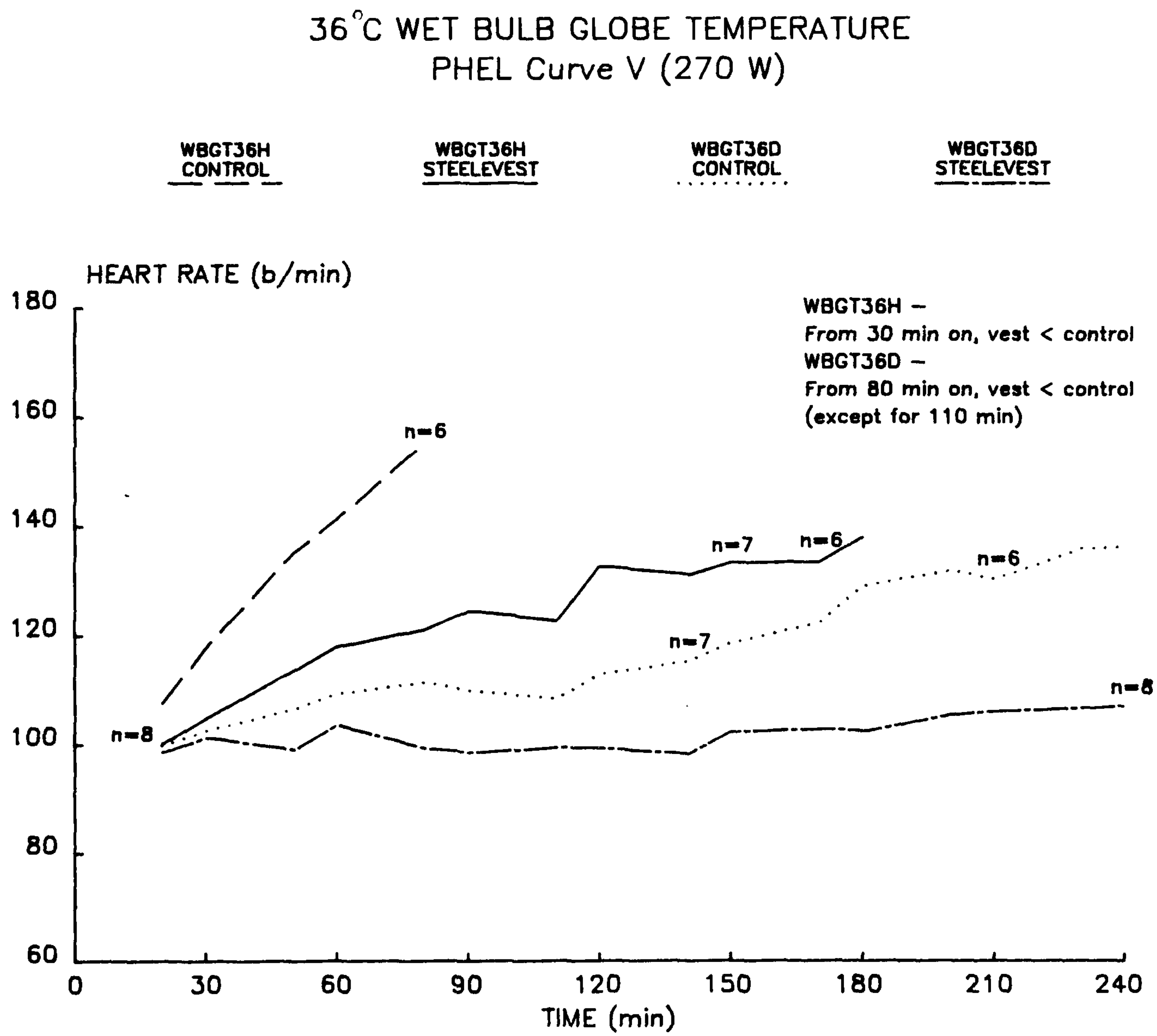


FIG. 9. Heart rate over time with and without the SteeleVest.

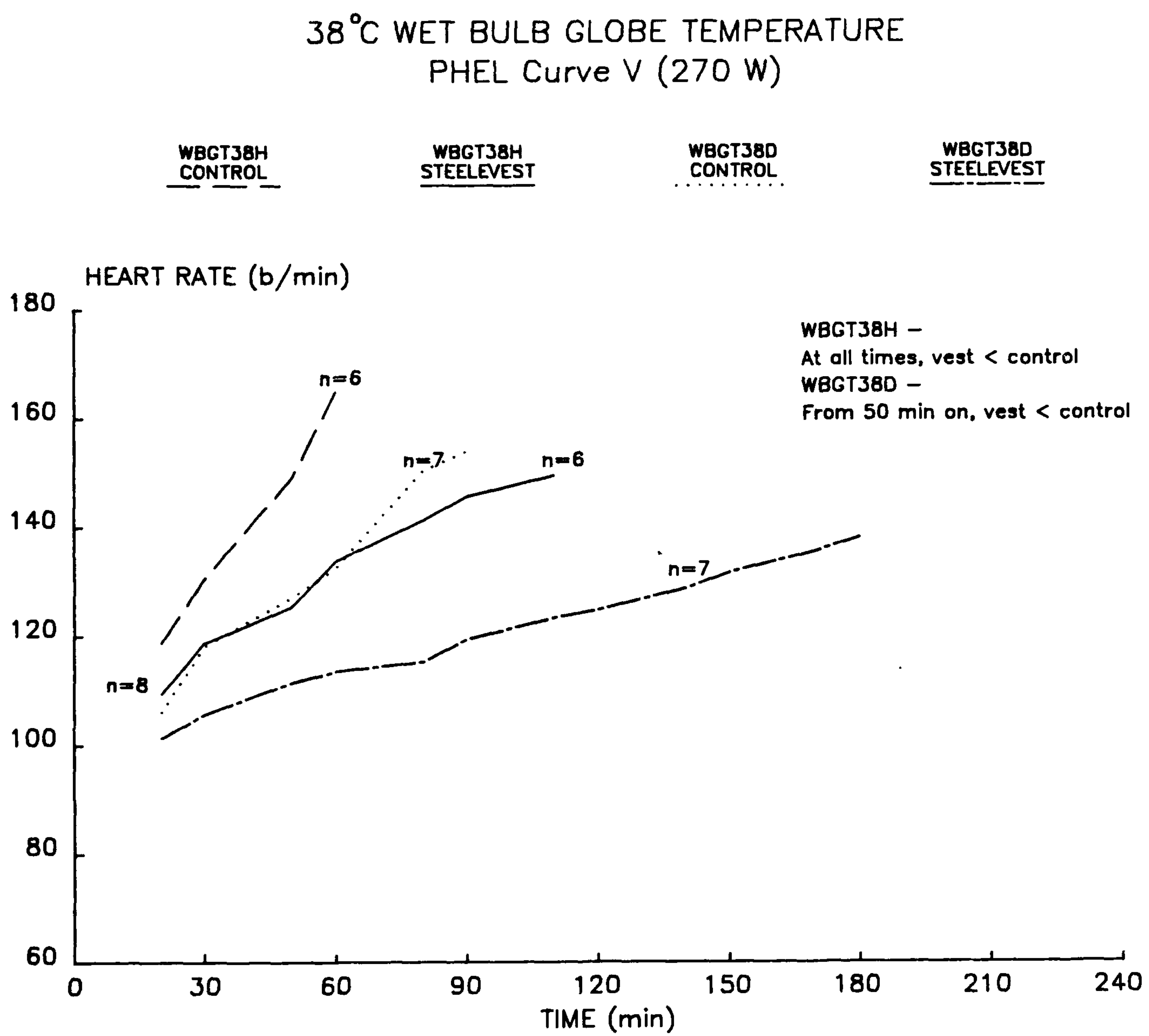


FIG. 10. Heart rate over time with and without the SteeleVest.

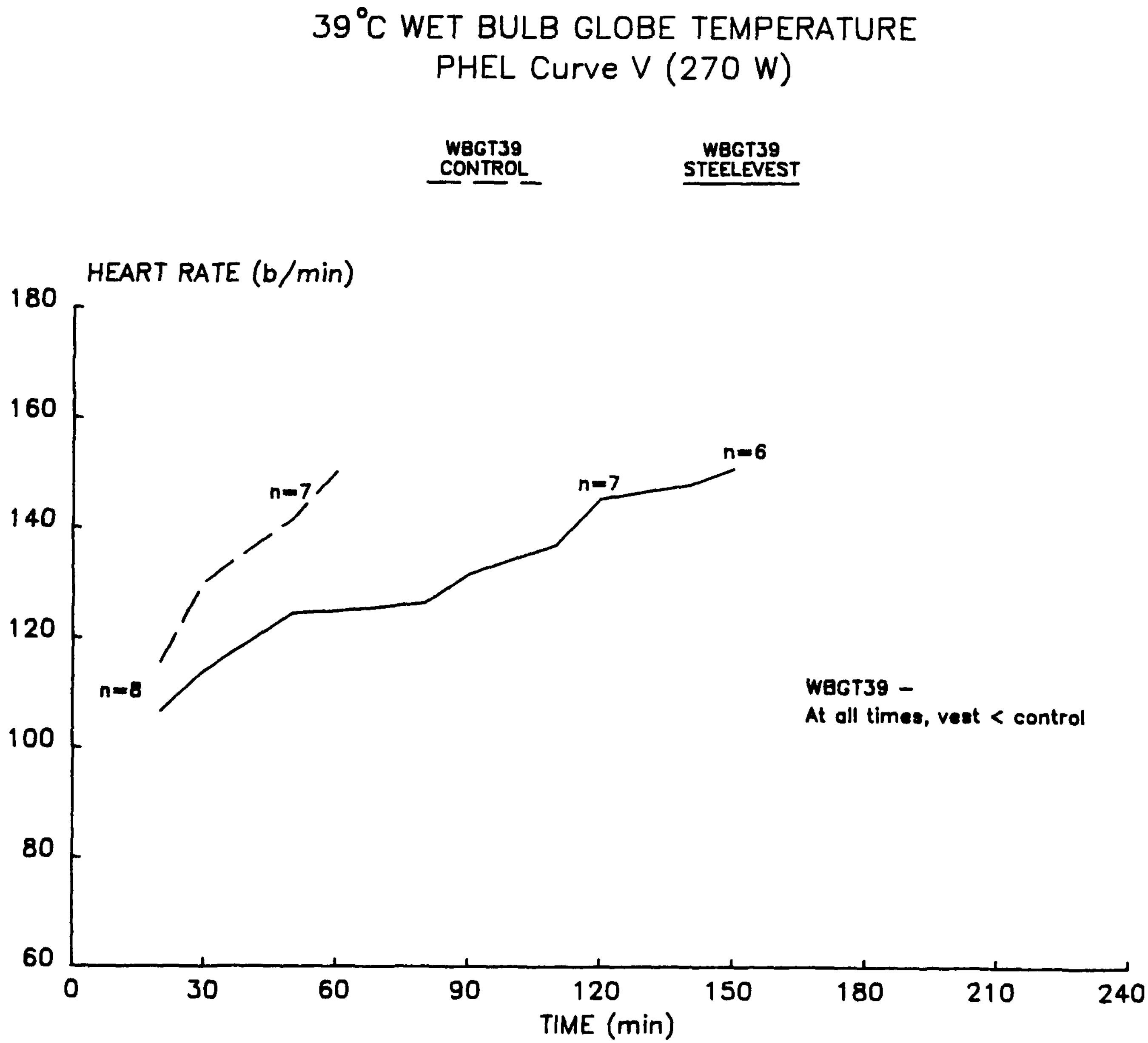


FIG. 11. Heart rate over time with and without the SteeleVest.

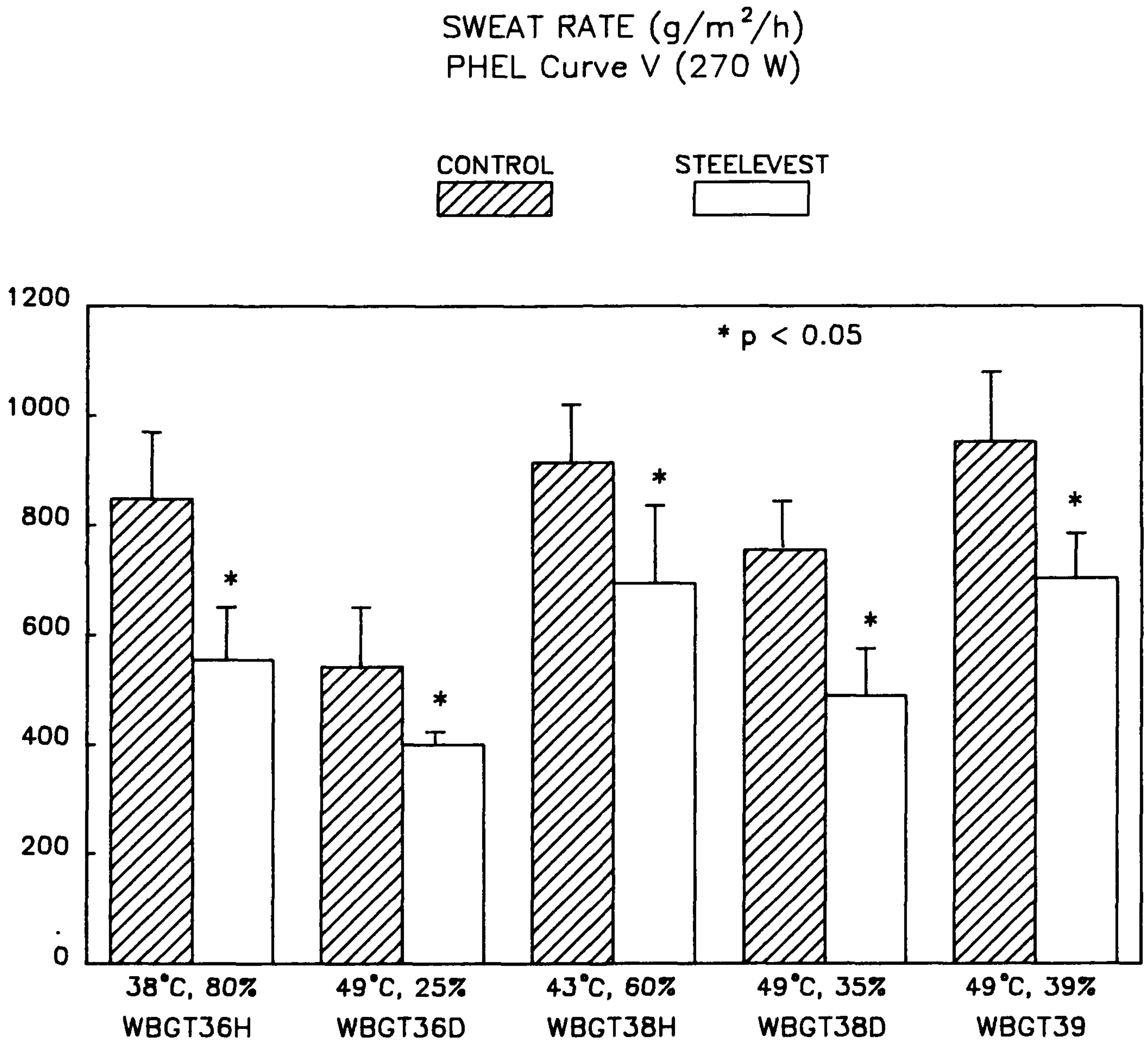
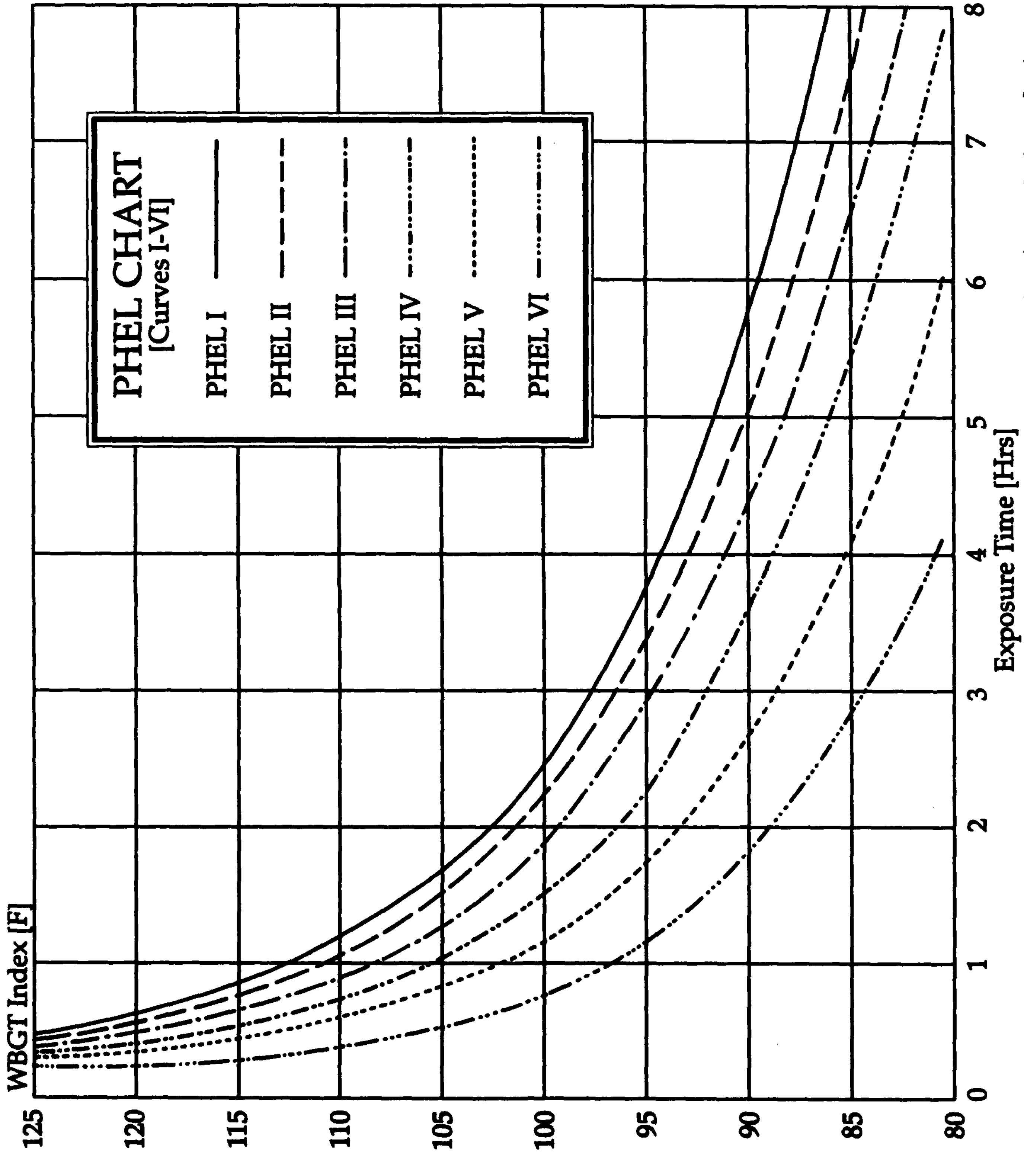


FIG. 12. Total body sweat rate with and without the SteeleVest. T indicates SD.

Appendix B. PHEL Chart (2).



From: U.S. Navy. <u>Manual of Naval Preventive Medicine.</u> Chapter 3, Ventilation and thermal stress ashore and afloat. <u>NAVMED P-5010-3</u> (1988), Naval Medical Command, Washington, D.C.

Appendix C. Tables of results.

Table 1. Average exposure times (± SD).

	WBGT36H	WBGT36D	WBGT38H	WBGT38D	WBGT39
Control	93	222	66	111	80
	(±25)	(±37)	(±9)	(±26)	(±17)
SteeleVest	213	240	123	214	178
	(±40)	(±0)	(±19)	(±39)	(±37)

Table 2. Absolute and change in rectal temperatures from initial to final values. Values are final for each test (see Methods).

	WBGT36H	WBGT36D	WBGT38H	WBGT38D	WBGT39
	Change in Rectal Temperature (°C)				
Control	1.9	1.4	1.8	1.8	1.9
	(±0.3)	(±0.4)	(±0.2)	(±0.2)	(±0.2)
SteeleVest	1.2	0.7	1.2	1.0	1.1
	(±0.2)	(±0.3)	(±0.3)	(±0.3)	(±0.2)
	Absolute Rectal Temperature (°C)				
Control	38.7	38.2	38.6	38.6	38.7
	(±0.2)	(±0.2)	(±0.3)	(±0.2)	(±0.2)
SteeleVest	37.9	37.6	38.1	37.9	38.0
	(±0.2)	(±0.2)	(±0.2)	(±0.3)	(±0.2)

Table 3. Mean weighted skin temperatures. Values are final for each test condition (see Methods).

	WBGT36H	WBGT36D	WBGT38H	WBGT38D	WBGT39
Control	37.3	36.8	38.1	37.6	37.8
	(±0.5)	(±0.4)	(±0.4)	(±0.5)	(±0.6)
SteeleVest	33.7	34.3	33.8	33.3	33.0
	(±2.1)	(±0.7)	(±1.4)	(±1.4)	(±2.5)

Table 4. Heart rates. Values are final for each test condition (see Methods).

	WBGT36H	WBGT36D	WBGT38H	WBGT38D	WBGT39
Control	155	132	165	154	150
	(±12)	(±16)	(±13)	(±18)	(±13)
SteeleVest	121	105	134	119	125
	(±13)	(±13)	(±11)	(±16)	(±11)

Table 5. Total body sweating rates.

	WBGT36H	WBGT36D	WBGT38H	WBGT38D	WBGT39
Control	848	542	914	755	953
	(±119)	(±97)	(±98)	(±88)	(±128)
SteeleVest	555	400	694	489	703
	(±92)	(±28)	(±144)	(±84)	(±86)

Table 6. Thermal sensation ratings. Values are final for each test condition (see Methods).

	WBGT36H	WBGT36D	WBGT38H	WBGT38D	WBGT39
Time (min)	60	240	60	90	60
Control	3.5	3.3	3.8	3.9	4.0
	(±0.8)	(±0.5)	(±0.3)	(±0.4)	(±0.4)
SteeleVest	2.8*	2.5*	3.2	2.9*	3.1*
	(±0.7)	(±0.5)	(±0.7)	(±0.4)	(±0.8)

* $p<0.05$ (SteeleVest < control)